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uvby PHOTOMETRY OF BLUE STRAGGLERS IN NGC 7789

BRUCE A. TWAROG
Department of Physics and Astronomy, University of Kansas, Lawrence, Kansas 66045

NEIL TYSON
Department of Astronomy, University of Texas, Austin, Texas 78712
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ABSTRACT

uvby photometry of 28 blue stragglers in the open cluster NGC 7789 is presented and analyzed. A rediscussion of the fundamental cluster parameters leads to $E(B-V) = 0.31 \pm 0.03$, [Fe/H] relative to the Hyades of -0.25 ± 0.10, $(m-M) = 12.3 \pm 0.3$, and an age of $1.6 \pm 0.5 \times 10^9$ yr on the isochrone scale of Ciardullo and Demarque (1977). Comparison of these results with those from the blue stragglers indicates that standard photometric calibrations do apply to the stragglers. It is found that the extended halo of blue stragglers around NGC 7789 is composed predominantly of field stars, and that the radial distribution of the stragglers is similar to that of the red giants, implying that the progenitors of both classes of star have the same mass, i.e., single stars near the cluster turnoff. When combined with weak photometric evidence for a lower bound to the luminosity distribution of the stragglers in the cm diagram, it is concluded that the best current model for these enigmatic stars is that of a single star which has mixed internally, as delineated in the work of Saio and Wheeler (1980). Possibilities for future research are outlined.

I. INTRODUCTION

Though astrophysics is no stranger to enigmatic objects, few have proven as resilient to attempts to probe their nature as the blue stragglers. For over twenty years, the position of these stars in the color-magnitude (cm) diagrams of open clusters and, more recently confirmed (Chaffee and Ables 1983) globular clusters, blueward and brighter than the cluster turnoff has presented a challenge to standard stellar-evolution theory. Ignoring the simple, but extremely difficult to test, solution that they represent a second generation of star formation within the clusters, explanations for the apparent extended lifetimes of the stragglers have concentrated on anomalous evolution of two types: (a) binary mass transfer (McCrea 1964; Van den Heuvel 1968); (b) internal mixing and/or coalescence (Wheeler 1979a,b; Saio and Wheeler 1980).

Detailed discussion of these possibilities may be found in Wheeler (1979a,b) and Trimble (1980). Generally, investigations of the problem have focused on two aspects of the solutions (a) and (b), the percentage of binaries among the stragglers, crucial to (a), and the spectroscopic and photometric "normalcy" of the stragglers when compared with nonstragglers of the same spectral type, with effects possibly produced in either (a) or (b). To date, the results have been contradictory. A high incidence of radial-velocity variation has been claimed among blue stragglers in NGC 7789 by Strom and Strom (1970, hereafter referred to as SS) and M67 by Peterson, Carney, and Latham (1984), while exactly the opposite conclusion has been reached by Hintzen, Scott, and Whelan (1974) for NGC 6633, NGC 6475, and NGC 752 and Stryker and Hrivnak (1984) for NGC 7789.

As for photometric and spectroscopic investigations, the results are again mixed. No evidence of periodic photometric variations has been produced for the stragglers (Hrivnak 1977), though little is expected for (a) since the companion should be an evolved star of much lower luminosity than the straggler. The work of Peterson, Carney, and Latham (1984) in M67 using a photometric technique for binary detection (Carney 1982, 1983) strongly supports the binary hypothesis. Most studies (e.g., Strom, Strom, and Bregman, 1971; Breger 1982) have indicated that the stragglers appear normal relative to stars in the same region of the cm diagram, while Mermilliod (1982), using a composite cm diagram of young open clusters, has claimed a high percentage of peculiar stars (50%) among the stragglers in these clusters, not atypical of the percentage among early-type stars.

Two questions of importance in any study of the stragglers in clusters are: (1) are they cluster members, and (2) how does one define abnormal? The first question is crucial because of the small number of stragglers found in most clusters. Statistically useful samples are hard to come by, and the subset of clusters with adequate membership information (proper motion and radial velocity) is substantially smaller. Often exclusion of one or two stars would alter the conclusion of an investigation. One recent example is the membership of F81 in M67. It is the most extreme (brightest) blue straggler in the cluster with a mass estimate at greater than twice the turnoff mass. It has been used as an example, among others, as evidence against the binary mass transfer hypothesis because of its high mass (Wheeler 1979b; Breger and Wheeler 1980; McNamara 1980). The argument is moot if such stars are nonmembers as recently claimed by Eggen (1981) for F81 on photometric grounds. This leads directly to the second question, the definition of abnormality. The importance of the luminous blue stragglers may be illusory if the evolution is truly anomalous, since the mass estimates are derived from comparisons with theoretical models of normal stars, a point which can also be made about membership determination with standard photometric and spectroscopic calibration as noted by Eggen (1981) and Mermilliod (1982).

The approach taken in the current investigation is based upon three plausible but, to varying degrees, debatable assumptions:

(1) all blue stragglers are formed by the same mechanism. Star-to-star variations in position in the cm diagram are due to the varying effectiveness of the mechanism and/or application of the mechanism to stars of differing mass.

(2) the effect of the mechanism is to alter the structure of

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the star in a way that leads to significant deviation of the star's evolution from that normally followed by a star of similar mass.

(3) the change in structure is reflected in the star's appearance through atmospheric anomalies and/or surface gravity-temperature changes which are detectable with standard photometric and spectroscopic techniques.

The third point should not be construed as a requirement that the stragglers demonstrate physically implausible combinations of temperature, surface gravity, composition, and luminosity for their position in the cm diagram. While atmospheric anomalies might produce such easily detectable discrepancies (e.g., Am stars), if the stragglers have undergone some systematic structural change, it is probable that the astrophysical parameters of interest will have undergone internally consistent adjustments that do not produce easily observable discrepancies compared to normal stars. The hope is that the stragglers will exhibit a nonrandom combination of plausible astrophysical parameters, which points to the cause of their existence.

Given the requirements of a large statistical sample, membership information, and the limitations of a small telescope, the obvious choice for the study was NGC 7789. Since the original study by Burbidge and Sandage (1958), it has been known that the cluster contains almost 30 blue straggler candidates. Proper-motion membership data are available from a number of studies (Cannon 1970; Pendl 1975) with the most recent survey of McNamara and Solomon (1981) being the best, a point confirmed by Breger (1982) using a polarization technique. One of the most interesting results of this proper-motion study was the discovery by McNamara (1980) of a class of blue stragglers that formed an extended halo about NGC 7789. If real, such a distribution would be an important clue to the nature of these stars. Finally, a limited amount of radial-velocity data was available from the work of Stryker and Hrivnak (1984).

Because most of the stragglers in this cluster were in the late B through A star range, *uvby* photometry was chosen as the best approach to search for coherent patterns within the sample. Ideally, Hβ photometry would provide more information in combination with *uvby* over this region of transition in the four-color calibrations (Crawford 1978, 1979). However, the faintness of the stars made such observations impossible with the equipment available. Section II presents the observations, Sec. III contains an analysis of the "normal" cluster parameters independent of the blue straggler data, Sec. IV discusses the analysis of the blue straggler photometry, and Sec. V summarizes the conclusions and details possible future approaches to the question.

II. THE DATA

a) Observations

Four-color observations were carried out in seven observing runs at McDonald Observatory between 1980 September and 1982 August using a single-channel, pulse-counting photometer attached to the 36-in. (91-cm) telescope. The photometer was fitted with an AMP56-DVP phototube operated at ambient temperature and an automated filter wheel containing a standard set of *uvby* filters. Because of poor weather conditions, the program was limited to 14 complete nights and nine nights of partial photometry. The same phototometer and filters were used on all nights.

Between 16 and 30 standard stars were observed on each complete night of photometry, with 18 being the average. On partial nights, the number was reduced to ten, on average. Because of the brightness limit of the phototube, standard stars were taken from the four-color catalog of Gronbech and Olsen (1976). Due to the large difference in magnitude between the standards and program stars, observations were made of the open cluster NGC 752 as a check on the calibration procedure. The results of this comparison have been discussed previously (Twarog 1983).

The observing procedure for the standard stars and the brighter program stars was similar. For the standards, each star was observed through two complete cycles of the filters, followed by a single cycle on sky. For the fainter program stars, this sequence was repeated until the star counts relative to sky achieved a statistical accuracy of 2% or better in each filter. Integration times for each filter were set that the total count rate in each filter was approximately the same. For *uvby*, this amounted to 30, 15, 15, and 20 s, respectively. On one night of each run, a pair of standard stars was observed over a wide range of air mass from four to six times to allow determination of extinction coefficients which were then used in the reduction of all nights for that run.

The reduction procedure adopted is the same as that in Twarog (1984) and will not be repeated. The final photometric results for the stars in NGC 7789 are presented in Table I, where column (1) contains the identification on the system of McNamara and Solomon (1981), column (2) lists the identification number on the system of Kustner (1923), columns (3)–(10) present the color indices and the standard deviation for a single observation for each index in the order V, $b-y$, m_1, and c_1, and column (11) is the number of observations. For those stars that have only one observation, the standard deviations have been set to 0.00, while for those stars with only two, one-half the difference between the two observations has been used.

b) Photometric Accuracy and Comparison to Earlier Work

Typical rms scatter of the standard stars about the calibration curves amounted to ± 0.005, ± 0.009, ± 0.011, and ± 0.010 mag for $b-y$, m_1, c_1, and V, respectively. However, given the faintness of the program stars (all $V > 10.5$) relative to the standards (all $V < 8.5$), a more reliable estimate of the photometric uncertainty can be gained by a look at the standard deviation among multiple observations of the same program star. For the 19 stars with two or more observations, the average standard deviations are ± 0.009, ± 0.012, ± 0.015, and ± 0.015 for $b-y$, m_1, c_1, and V, respectively. As illustrated in Fig. 1, the standard deviations remain effectively constant over the magnitude range from $V = 10.5$ to $V = 13.75$.

Despite the apparent interest in the blue straggler phenomenon, surprisingly little comprehensive photoelectric work has been done on NGC 7789. For broadband photoelectric photometry, the best study to date has been that of Breger (1982) on the *UBV* system. For 13 stars common to the two samples, the mean difference in V in the sense (TT − Breger) is 0.00 ± 0.02. Breger's analysis shows he is on the same V system as Janes (1977a), whose study emphasized the cluster red giants, and confirms a systematic error of 0.06 mag in the photographic study of Burbidge and Sandage (1959) (hereafter referred to as BS).

For the *uvby* system, the only possible comparison is with the survey of SS. For the six stars common to the two studies, the mean differences in the sense TT − SS are -0.019 ± 0.009, 0.000 ± 0.012, and 0.003 ± 0.067 for

TABLE I. *uvby* photometry of blue stragglers.

ID No.	Alternate ID	$V \pm$ s.d.	$b-y \pm$ s.d.	$m_1 \pm$ s.d.	$c_1 \pm$ s.d.	N
M99		11.93 ± 0.01	0.306 ± 0.005	0.121 ± 0.008	0.838 ± 0.007	4
M144		13.56 ± 0.00	0.384 ± 0.000	0.057 ± 0.000	0.940 ± 0.000	1
M172		12.06 ± 0.01	0.374 ± 0.007	0.109 ± 0.011	0.579 ± 0.021	4
M210		12.91 ± 0.04	0.338 ± 0.013	0.112 ± 0.012	0.714 ± 0.008	6
M238		12.41 ± 0.01	0.273 ± 0.011	0.140 ± 0.002	0.810 ± 0.001	2
M257	K2	13.34 ± 0.03	0.386 ± 0.015	0.096 ± 0.016	0.535 ± 0.010	4
M317	K68	13.67 ± 0.00	0.234 ± 0.000	0.097 ± 0.000	1.240 ± 0.000	1
M325	K88	13.10 ± 0.02	0.298 ± 0.003	0.081 ± 0.002	1.150 ± 0.004	3
M396	K197	13.38 ± 0.00	0.278 ± 0.000	0.137 ± 0.000	1.175 ± 0.000	1
M459		11.59 ± 0.01	0.188 ± 0.012	0.061 ± 0.016	0.949 ± 0.027	6
M460	K282	12.06 ± 0.01	0.196 ± 0.020	0.068 ± 0.018	1.232 ± 0.027	2
M482	K316	13.80 ± 0.00	0.253 ± 0.000	0.120 ± 0.000	1.076 ± 0.000	1
M502	K342	12.41 ± 0.02	0.186 ± 0.002	0.048 ± 0.014	1.000 ± 0.032	3
M511		10.98 ± 0.02	0.154 ± 0.008	0.079 ± 0.012	0.899 ± 0.022	6
M518	K371	12.94 ± 0.01	0.262 ± 0.008	0.112 ± 0.031	1.209 ± 0.018	2
M543	K409	12.96 ± 0.00	0.229 ± 0.000	0.109 ± 0.000	1.057 ± 0.000	1
M574	K453	12.64 ± 0.03	0.198 ± 0.003	0.040 ± 0.017	0.842 ± 0.020	3
M747	K677	11.15 ± 0.01	0.144 ± 0.008	0.061 ± 0.010	0.994 ± 0.007	6
M752	K696	13.78 ± 0.01	0.232 ± 0.020	0.024 ± 0.001	1.083 ± 0.013	2
M789	K746	12.77 ± 0.02	0.265 ± 0.008	0.097 ± 0.015	1.152 ± 0.009	3
M808		13.08 ± 0.01	0.221 ± 0.005	0.147 ± 0.015	1.058 ± 0.002	3
M913	K934	13.05 ± 0.00	0.207 ± 0.008	0.156 ± 0.011	0.908 ± 0.020	2
M1054	K1168	13.90 ± 0.00	0.327 ± 0.000	0.080 ± 0.000	1.094 ± 0.000	1
M1060		10.77 ± 0.00	0.223 ± 0.006	0.126 ± 0.001	1.084 ± 0.028	2
M1088	K1211	11.55 ± 0.01	0.142 ± 0.011	0.060 ± 0.010	0.595 ± 0.014	6
M1133	K1270	13.46 ± 0.00	0.311 ± 0.000	0.129 ± 0.000	1.057 ± 0.000	1
M1142	K1288	13.00 ± 0.00	0.248 ± 0.000	0.011 ± 0.000	1.074 ± 0.000	1
M1251		12.76 ± 0.00	0.498 ± 0.000	0.078 ± 0.000	0.646 ± 0.000	1

$b-y$, m_1, and c_1, respectively. Because of the small sample size and the disturbingly large scatter in c_1, no attempt will be made to combine the two samples. A seventh star, K1168, was dropped from the comparison because it appears that SS observed the wrong star. The V magnitude given for this star in Table 5 of SS is 13.2, while the present study and that of Breger (1982) both obtain 13.9. BS did not include this star in their photographic survey and no source for the magnitude or color is listed by SS. These incorrect values have been adopted in the analysis by McNamara (1980). This error may explain why K1168 appeared anomalous in the discussion of SS. Saio and Wheeler (1980) have suggested that SS observed K1163, a star near K1168 with the appropriate magnitude and colors.

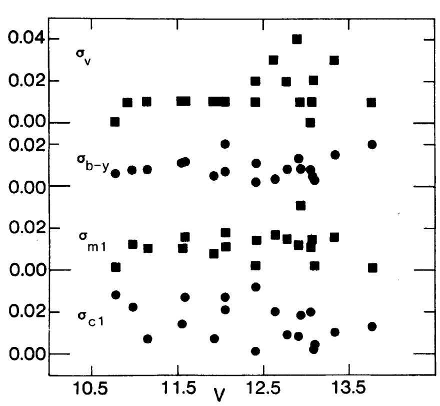

FIG. 1. Standard deviations of a single observation for *uvby* photometry of Table I as a function of apparent visual magnitude.

III. CLUSTER PARAMETERS

Before we begin the discussion of the photometry of Table I in our search for a defining characteristic or anomaly which might distinguish the blue stragglers from "normal" stars, it is important first to establish what normal is for NGC 7789. By this we mean the fundamental characteristics of the cluster, reddening, metallicity, age, and distance, as determined by the nonstraggler members. Unfortunately, because they are usually the brightest main-sequence stars in the cluster, it is not uncommon for the blue stragglers to be used to derive the cluster parameters with the implicit, *ad hoc* assumption that the standard calibrations are applicable. NGC 7789 is no exception.

Reddening determinations for this cluster have been discussed in detail by Breger and Wheeler (1980). Of the estimates in the literature ranging from $E(B-V)=0.23$ to 0.34, BS, SS, and Arp (1962) include the blue stragglers in their derivations, while only Janes' (1977a) DDO study of the red giants does not. (In the analysis of BS and Arp (1962), just over half of the blue stars are nonmember, foreground stars and should provide a reliable lower limit to the reddening using standard two-color relations.) To avoid a circular argument on the normality of the blue stragglers, it would be best to derive this parameter independent of them. Once done, standard calibrations can be applied to the stragglers to determine if they produce a similar result.

This would appear to leave us with only the choice of adopting the DDO result of Janes (1977a,b), a valid but not completely secure solution given the possible large uncertainties associated with the reddening calibration of the system. Alternatively, one could use UBV photometry of the giants (BS; Jennens and Helfer 1975, hereafter referred to as JH) to derive a reddening, but this requires *a priori* knowledge of the cluster metallicity. To obtain the reddening while making optimal use of the available photometry, the following procedure was adopted. The assumed reddening was varied between $E(B-V)=0.25$ and 0.35. Appropriate corrections were applied to the DDO and *UBV* giant star photometry, and a metallicity was obtained from each; the DDO system is based upon a CN index, while the ultraviolet excess of the *UBV* system is defined predominantly by Fe lines. The slopes of the metallicity calibrations are well determined for both systems (Janes 1975; Carney 1979; Wallerstein and Helfer 1966), and the Hyades cluster is selected as the relative standard to avoid arguments over the zero-point shift to a system defined relative to the Sun. Reddening corrections affect the two photometric systems differently. If we require that the metallicity derived from both systems be the same, a unique reddening value and metallicity results by adjusting the reddening until this requirement is met. While a difference in metallicity based upon CN, as compared with that from Fe, has been found in some globular clusters, there is strong evidence that such anomalies are rare among open clusters (Smith 1982) and that CN and Fe are well correlated (McClure and Twarog 1978).

To maintain a high level of accuracy, only *UBV* photoelectric photometry was used in the analysis. As discussed by Janes (1977a), his $B-V$ data are in excellent agreement with that of BS, while a correction of 0.05 mag must be applied to the V data of BS to bring it onto the system of Janes. For stars common to the two systems, this was done and the results averaged. This combined sample (BSJ) was then compared with that of JH. For the nine stars common to the two samples, the mean differences in V and $B-V$ were found to be -0.027 ± 0.017 and 0.018 ± 0.028, respectively, in the sense (JH − BSJ). These corrections were applied to the data of JH, and the results averaged with BSJ. For $U-B$ the situation is much more uncertain. JH and BS have only three stars in common, with an average difference of -0.023 ± 0.091, in the sense (JH − BS); Janes (1977a) did not observe in U. For two stars, only the data of BS are available, while the results of JH were adopted for the remaining 12, an encouraging point since earlier work has shown the *UBV* data of JH to be quite reliable (Twarog 1983). Two additional stars, M315 and M946, the reddest of the giants in the sample, were dropped from the analyses because their colors produced anomalously discrepant ultraviolet excesses, independent of which reddening value was chosen.

The color-color diagram for the red giants is shown in Fig. 2. Light circles identify the three stars for which no cluster membership information is available. The solid line is the two-color relation for Hyades group giants (Eggen 1966) adjusted for a reddening of $E(B-V)=0.25$. The short and long dashed lines are the same relation for assumed reddenings of $E(B-V)=0.30$ and 0.35, respectively. The reddening slopes as a function of color have been taken from the work of Crawford and Mandwewala (1976). For the DDO metallicity, the indices of Janes (1977a) were used and a mean δ CN calculated for each of the assumed reddening values. The average δ CN and $\delta(U-B)$ indices for 19-member and 16-member giants are presented in Table II, while the indices transformed to [Fe/H] relative to the Hyades are plotted in Fig. 3. If we require similar metal-abundance determinations from the two indices, $E(B-V)=0.31\pm0.03$, and [Fe/H] $=-0.25\pm0.10$ relative to the Hyades. Use of $E(B-V)=0.24$ leads to a discrepancy of -0.3 in $[Fe/H]_{DDO}$ compared to $[Fe/H]_{UBV}$.

With the reddening and metallicity known, we can derive

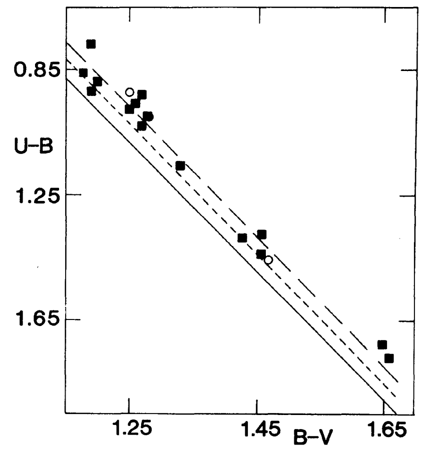

FIG. 2. Two-color *UBV* diagram for red giants in NGC 7789. Light circles are stars without membership information. Solid, short-dashed, and long-dashed lines are the Hyades group giants' relation (Eggen 1966) adjusted for a reddening of $E(B-V)=0.25$, 0.30, and 0.35, respectively.

an age estimate and use this as an indirect check on the reddening determination. The estimate will be done differentially relative to NGC 752. From the cm diagram of Breger (1982) or BS, the color of the main-sequence turnoff is estimated to be $(B-V)=0.60$, or $(B-V)_0=0.29$ for $E(B-V)=0.31$, and $(B-V)_0=0.36$ for $E(B-V)=0.24$. The comparable turnoff color for NGC 752 is $(B-V)_0=0.36$ (Twarog 1983). Taking into account the small metallicity difference between NGC 7789 and NGC 752 ([Fe/H] $=-0.25$ for NGC 7789 and -0.33 for NGC 752), and adopting the age-turnoff color relation from the isochrones of Ciardullo and Demarque (1979), NGC 7789 should be 5.5×10^8 yr younger than NGC 752 for the case of the larger reddening, and 1.5×10^8 for the smaller value. Since the lower reddening estimate would also produce a metallicity for NGC 7789 closer to NGC 752, the age difference would be effectively zero in this case.

We can now estimate the true relative age difference between the clusters using a reddening- and metallicity-independent technique called the morphological age ratio (MAR). For a detailed description, the reader is referred to the Appendix of Anthony-Twarog and Twarog (1985). In short, the difference in magnitude between the red giant clump and the top of the main-sequence turnoff is divided by the color difference between the giant branch at the level of the clump and the main-sequence turnoff. The result is called the MAR, and is found to be linearly correlated with age over the calibrated range of 1×10^9 yr to 7×10^9 yr on the isochrone scale of Ciardullo and Demarque (1977). The slope of the calibration is 1.4. Using the precepts outlined in Anthony-Twarog and Twarog (1985), for NGC 7789 the turnoff has $(B-V)=0.60$ and $V=13.70$, and the giant branch at the level of the clump has $(B-V)=1.35$ at $V=12.85$, giving a MAR of 1.13. For NGC 752, MAR = 1.46, equivalent to an age difference of 4.5×10^8 yr. Thus, while it seems likely that NGC 7789 is younger than NGC 752 by an amount consistent with a reddening of $E(B-V)=0.31$, the uncertainties in the technique are such that $E(B-V)=0.24$ cannot be excluded definitively in this way.

TABLE II. Metallicity comparison for different assumed reddenings.

$E(B-V)$	0.25	0.30	0.35
δ CN $\pm$ (s.e.m.)	-0.003 ± 0.009	0.017 ± 0.008	0.037 ± 0.007
$\delta(U-B) \pm$ (s.e.m.)	0.12 ± 0.01	0.06 ± 0.01	0.01 ± 0.01

The final parameter of interest for NGC 7789 is the distance. The classical technique for open clusters is main-sequence fitting but, though it has been attempted, such an approach is futile for NGC 7789. The combination of low photometric accuracy in BV and the inability of BS to adequately reach the unevolved main sequence leads to prohibitive errors in the distance modulus. The only direct photometric technique not involving the blue stragglers is the use of DDO photometry as in Janes (1977a), who derived $(m-M)_0 = 11.6 \pm 1.1$ (s.d.) from 20 stars assuming $E(B-V) = 0.24$. This sample has been reanalyzed using $E(B-V) = 0.31$. Excluding three stars that fall outside the calibration range and K466, a nonmember, the absolute-magnitude calibration of Janes (1975) leads to $(m-M) = 11.9 \pm 1.0$ (s.d.) for 18 stars or $(m-M)_0 = 10.9$. The difference in the apparent moduli is only 0.5 mag because of the lower reddening adopted by Janes (1977a). Though the systematic change in distance is significant, the reliability of either value on an absolute scale is not. The moduli show an unusually large dispersion which may reflect a real scatter in the properties of the giants (Palmer and Wing 1983) or uncertain photometry, and Janes (1979) has called into question the validity of the zero point of the absolute-magnitude calibration of the DDO system.

An indirect but more reliable technique is to make use of the absolute magnitude of the red giant clump. As detailed in Twarog (1983), a cluster the age of NGC 7789 should have $M_V = 0.6 \pm 0.2$, slightly less than that of NGC 752. Using $m_v = 12.9$ for the clump leads to $(m-M) = 12.3 \pm 0.3$ for NGC 7789.

IV. THE BLUE STRAGGLERS

a) Reddening Determinations: UBV Photometry

Adopting $E(B-V) = 0.31$ as the reddening for NGC 7789, we can now use the blue straggler photometry to test for consistency with this value. The first comparison will include the UBV data because, for hotter stars, the standard broadband indices are very weakly dependent upon variations in the two properties most likely to exhibit anomalies among the blue stragglers, the metallicity and the surface gravity. Only extremes such as white dwarfs, supergiants, horizontal-branch stars, and metallic-line stars show significant deviations from the standard two-color relations.

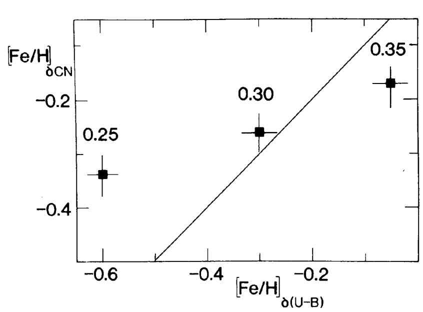

FIG. 3. Comparison of [Fe/H] relative to the Hyades as deduced from DDO photometry with that obtained from the UBV indices for assumed reddening values of $E(B-V) = 0.25$, 0.30, and 0.35.

Ideally, one would prefer to use only photoelectric data in such an analysis. However, the degree of overlap among the various surveys is often small and, particularly in the case of the blue stragglers, only photographic data are available for some stars. A comprehensive transformation of all the photometry will be attempted. The data considered were the V photometry of the present investigation, the photoelectric UBV photometry of Breger (1982), the photoelectric and photographic results of BS, and the photographic data of McNamara (1980). A preliminary analysis of the last data sample demonstrated a strong color gradient as a function of east-west position, so the photometry was deleted from the final analysis; the details of this analysis will be discussed below.

As noted earlier, the V photometry of Breger (1982) and the present study are on the same system, while the data of BS include a systematic difference of 0.06 mag relative to Breger. A more detailed comparison reveals that the differences are strongly correlated with color. The V magnitudes of BS were transformed to the system of Breger using the following relation:

$$V_{\rm BR} = V_{\rm BS} + 0.15^*(B-V)_{\rm BR}.$$

The transformed photometry was then combined with the photoelectric data giving each of the photoelectric measurements full weight, and the photographic data, half weight.

For B, this procedure proved inadequate. By dropping the results of McNamara (1980) from the analysis, a number of stars discovered to be proper-motion members in the cluster halo were without B data. V magnitudes were available because of the equivalence of y of the $uvby$ system and V; a comparable situation does not exist for b and B or v and B. To obtain some information on these stars, a photographic plate of NGC 7789 was taken with the 27-in. (69-cm) telescope of the Clyde Tombaugh Observatory of the University of Kansas. The observations consisted of a 6-min exposure of a IIa-O emulsion with a Schott GG-385 filter, providing a limited magnitude near $B = 15.5$. Forty stars, including 25 standard stars over a range in color, were measured with the Cuffey iris astrophotometer of the University of Kansas and transferred to the standard system of Breger after application of a color term of slope -0.07, typical for these emulsions. [The reader is referred to Anthony-Twarog, Twarog, and McClure (1978) for the details of the reduction procedure.] The rms scatter of the standard stars about the calibration curve was only $+0.025$ mag, but the uncertainty in the photometry for the extended halo stars is probably at least twice this value.

The B magnitudes of BS were transformed to the system of Breger with the addition of 0.07 mag; no correlation of the residuals with color was found in the transformation. The three sets of photometry were combined with the photoelectric data given full weight and the photographic data sets each given half weight. The combined B magnitudes were reduced then by 0.02 mag to ensure that the colors were on the same $B-V$ system as that of Janes (1977a) and BS. The final BV photometry is listed in columns (5) and (6) of Table III. Column (7) contains a quality class parameter Q, which ranges from 1 to 4. $Q=1$ identifies a star for which all possible photoelectric and photographic observations are available, $Q=2$ indicates that photographic data are absent for B and/or V, $Q=3$ implies that one of the photoelectric observations and one of the photographic observations are absent for B and/or V, and $Q=4$ identifies a star for which only the V magnitude of the current investigation and the B results from one photographic plate are available.

As a check of the reliability of the final $B-V$ colors, one can compare the observed $b-y$ of Table I with $B-V$ as illustrated in Fig. 4. For stars of the same metallicity, such a plot should show a strong correlation between the two indices, with a scatter dependent primarily upon the internal errors of the photometry. The effect of reddening is minor because with $E(b-y)/E(B-V)=0.73$ (Crawford 1979), reddening moves a star essentially parallel to the relation seen in Fig. 4. The Q parameter is designated in Fig. 4 by: dark circles, $Q=1$, dark triangles, $Q=2$, light triangles, $Q=3$, and light circles, $Q=4$. As expected, the photometric scatter is small for $Q=1$, and quite large for $Q=4$.

If such a figure is constructed using the photographic data of McNamara (1980) for the $Q=4$ stars, a positional color gradient is apparent across the cluster. Stars M99, M144, M172, M210, and M257 all lie too blue in $B-V$ for their $b-y$ colors by amounts ranging from $(B-V)=0.10$ mag

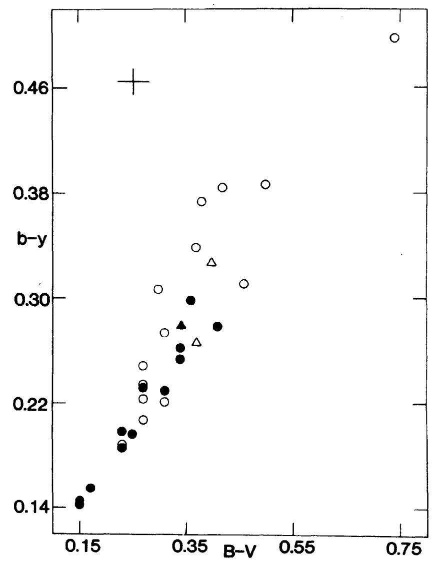

FIG. 4. Observed $b-y$ of Table I for NGC 7789 blue stragglers compared with derived $B-V$ of Table II. Symbols indicate quality parameters for $B-V$: $Q=1$, dark circles; $Q=2$, dark triangles; $Q=3$, light triangles; $Q=4$, light circles. Cross indicates errors of ± 0.01 in $b-y$ and ± 0.025 in $B-V$.

TABLE III. Relevant data on blue stragglers.

ID No.	Type[a]	PM[b]	$E(b-y)$	V	$B-V$	Q	$U-B$	Mem comment
M99	NA	86	0.230	11.93	0.30	4		NM C_1-$(b-y)$
M144	B?	67	0.420:	13.56	0.42	4		M? High $E(B-V)$
M172	NA	89	0.230	12.06	0.38	4		NM C_1-$(b-y)$
M210	NA	90	0.230	12.91	0.37	4		NM C_1-$(b-y)$
M238	NA	94	0.230	12.41	0.31	4		NM C_1-$(b-y)$; RV
M257	NA	98	0.230	13.34	0.50	4		NM C_1-$(b-y)$
M317	A	76	0.219	13.66	0.27	4		M
M325	A	98	0.278	13.09	0.36	1	0.30	M
M377	A	77	0.204	13.81	0.34	3	0.24	M *uvby* – SS; K168
M389	NA	52	0.230	13.63	0.32	3	0.33	M K192
M396	A	46	0.223	13.34	0.41	1	0.33	NM $P<50\%$
M459	B	90	0.219	11.59	0.23	4		M
M460	A	97	0.218	12.05	0.25	1	0.19	M
M482	A	98	0.198	13.80	0.34	1	0.27	M
M502	B	96	0.211	12.42	0.23	1	0.06	M
M511	B	98	0.189	10.98	0.17	4		NM RV
M518	A	98	0.222	12.95	0.34	1	0.23	M
M543	A	53	0.205	12.98	0.31	1	0.22	M
M574	B	98	0.237	12.66	0.23	1	−0.02	M
M747	B	53	0.169	11.16	0.15	1	−0.04	M? Low $E(B-V)$
M752	B	98	0.249	13.76	0.27	1	0.13	M
M789	A	98	0.241	12.75	0.37	2	0.29	M VAR?
M808	B(A)	94	0.238:	13.08	0.31	4		M? $E(B-V)=0.169$ if A
M913	B	78	0.241	13.05	0.27	4		M
M1054	A	95	0.298	13.91	0.40	2	0.33	M? High $E(B-V)$
M1060	B(A)	97	0.238:	10.77	0.27	4		NM RV; $E(B-V)=0.181$ if A
M1088	Ap	97	0.230	11.54	0.15	1	−0.32	M
M1133	A	98	0.242	13.46	0.46	4		M
M1142	B	92	0.265	13.00	0.27	4		M
M1251	NA	71	0.230	12.76	0.74	4		M

Notes to TABLE III

a—reddening calibration—B—Crawford (1978)
b—McNamara (1980)
A—Hilditch, Hill, and Barnes (1983)
NA—None Available

TABLE IV. Blue straggler apparent distance moduli.

Star ID (McNamara and Solomon)	$E(b-y) =$	$(m-M)$ 0.23	$(m-M)$ var	$(m-M)$ 0.18
144		11.95	B	12.77
317		13.44	13.57	13.85
325		12.46	12.03	12.95
377		$-\delta c_1$	12.15	12.39
396		12.83	12.34	13.21
460		B	12.73	11.97
482		12.13	12.42	12.60
518		12.70	12.71	12.97
543		$-\delta c_1$	11.18	11.45
752		B	B	12.50
789		11.96	11.83	12.28
808		B	B	11.49
1054		12.93	12.34	13.67
1133		12.01	11.97	12.64
1142		B	B	11.74
1251 (F star)		10.88	10.88	11.37
$\langle m-M \pm \text{s.d.}\rangle$	all stars	12.33 ± 0.71	12.18 ± 0.71	12.49 ± 0.75
$\langle m-M \pm \text{s.d.}\rangle$	deviants removed	12.37 ± 0.41	12.28 ± 0.31	12.64 ± 0.53

to 0.33 mag, with a mean of 0.21 mag. Such gradients are not uncommon in photographic work with an iris astrophotometer over large areas of a plate because of background variations and the usual concentration of standard stars near the cluster core. Such a discrepancy is seen in the results of the current study plotted in Fig. 4, but the same five stars range in color deviation from 0.04 to 0.14 mag, with an average residual from the mean relation of only 0.10 mag, significantly smaller than the data of McNamara. One could argue that the error lies with the $b-y$ data; however, all but one of these stars have multiple $b-y$ observations with internal errors an order of magnitude smaller than that required to explain the discrepancy, a point corroborated by the small internal scatter of the $Q = 1$ stars.

The $U-B$ colors were derived from the photoelectric photometry of Breger (1982) and BS. For eight stars common to the two samples, the mean difference in the sense (Breger − BS) is 0.06 ± 0.07. The photometry of Breger was adjusted by 0.06 mag and the samples combined. The resulting $U-B$ data are listed in column (8) of Table IV for 14 cluster members and one nonmember. An additional nine nonmembers are not listed. The *UBV* photometry for the 24 stars was corrected for a reddening of $E(B-V) = 0.31$ using the reddening slopes of Crawford and Mandwewala (1974) and is plotted in Fig. 5 relative to the standard relations for zero-age main-sequence stars (Eggen 1965). Light circles are members, while triangles are nonmembers. The nonmembership is based upon proper motion ($p < 50\%$), radial-velocity data (Hrivnak and Stryker 1984, private communication), and position in the *uvby* color-color plots (see Sec. IV*b*). On average, the stars scatter about the mean relation by an amount consistent with the photometric uncertainties. Adoption of $E(B-V) = 0.24$ and/or deletion of the adjustment of the $U-B$ colors of Breger to bring them onto the system of BS produces a noticeably worse fit. Thus, either $E(B-V) = 0.31$, or blue stragglers can be identified by a significant deviation from the standard two-color relation for hot dwarfs and cannot be used for reddening estimation. We feel that the former conclusion is more likely and is supported by the *uvby* data which will be discussed next.

b) Reddening Determinations: uvby Photometry

Before discussing the details of the reddening estimation using four-color photometry, a look at the c_1-$(b-y)$ diagram is in order. As a first approximation, we simply adopt $E(B-V) = 0.31$ from the *UBV* data and apply the appropriate dereddening corrections to the data of Table I. The value of this procedure is apparent in Fig. 6, where the standard relations for unevolved main-sequence stars from Crawford (1978, 1979) are also plotted. Light circles are nonmembers; the three nonmembers with dereddened c_1 indices greater than 0.85 have been classed as such on the basis of radial-velocity and/or proper-motion information. The remaining five, M99, 172, 210, 238, and 257, have been identified as nonmembers because of their unique position below the standard c_1-$(b-y)$ relation. As will be discussed below, the remaining 80% of the sample are located in positions consistent with normal or slightly lower than main sequence surface gravity. If the five stars were members, they would require anomalously high surface gravities, intrinsically low

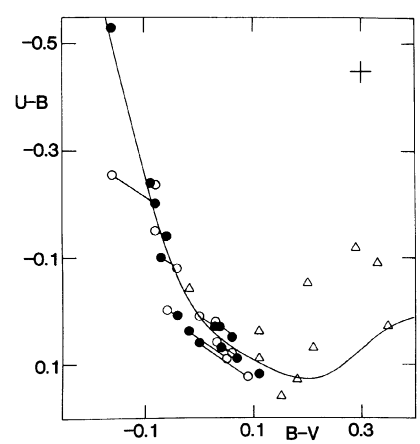

FIG. 5. Two-color *UBV* diagram for the blue stragglers in Table III. Light circles and triangles represent members and nonmembers, respectively, adjusted for $E(B-V) = 0.31$. Dark circles are members adjusted for the individual reddening corrections of Table III. The cross indicates the size of a ± 0.02 error in either index.

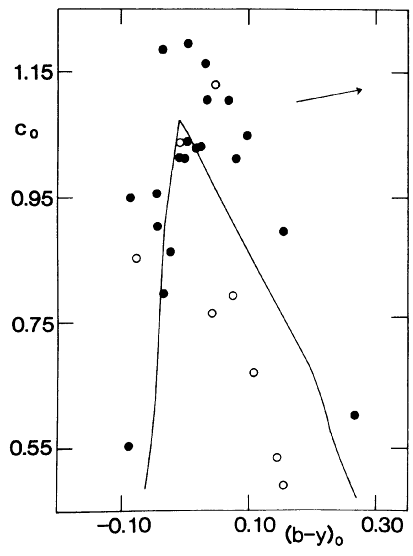

FIG. 6. c_0-$(b-y)_0$ diagram for the blue stragglers in NGC 7789. Light circles are nonmembers as identified in Table III. $E(b-y)=0.23$ has been assumed for all stars. Solid line is the standard relation for main-sequence B, A, and F stars. The arrow indicates the effect of a reddening of $E(b-y)=0.10$.

reddenings, an assumed cluster reddening that was too high, or a systematic error in the photometry for these stars. The first suggestion is considered unlikely since it affects only 20% of the sample. Either this anomaly is irrelevant to the blue straggler phenomenon, or we must violate our assumptions of Sec. I and postulate multiple origins for blue stragglers in different portions of the cm diagram. Given the positions of these anomalous stars in the extended halo of the cluster, the second possibility is viable. However, studies to date (BS; Breger 1982) have given no indication of variable reddening across the cluster; the amount required would be a deficiency of $E(B-V)=0.12$ in this region of the cluster. The third solution would require that the cluster have an actual reddening of $E(B-V)=0.20$ or less, rather than the assumed value of 0.31. Unfortunately, though this would move the anomalous stars to a reasonable position in the two-color diagram, it would place the hotter stars ($b-y$ less than 0.0) in an anomalous location, and ignores the result of the *UBV* two-color fit. It could be argued that this choice of one group of anomalous stars over another is a matter of personal preference; this is not the case. The location of the five stars listed above in the extended halo of the cluster and their apparent anomalously low reddening can most plausibly be explained by their being foreground stars, a conclusion which has been confirmed recently for one of the five through radial-velocity data (Hrivnak and Stryker 1984, private communication). M238 is a definite nonmember, while M172 has a radial velocity consistent with membership. Observations of the other stars would be valuable.

Finally, the possibility exists that the $b-y$ results for these stars are systematically too low, especially in light of our earlier claim that a number of these stars lie in anomalous positions in the $(b-y)$-$(B-V)$ plot of Fig. 5. This can be excluded because the error in Fig. 5 is in the opposite sense to that of Fig. 6; Fig. 5 indicates that the stars are too red for their $(B-V)$ color. It will be assumed for the remainder of the discussion that these stars are nonmembers.

Reddening calibrations for early-type stars on the *uvby* Hβ system can be found in a number of investigations (Crawford 1975, 1978, 1979; Claria 1974; Hilditch, Hill, and Barnes 1983). We have adopted the procedures of Crawford (1978) for B stars, and those of Hilditch *et al.* (1983) for intermediate A stars, where small systematic errors in the earlier work of Crawford (1979) and Claria (1974) have been corrected. Cooler stars in the sample ($b-y$ greater than 0.06) require Hβ, which is not available for the stars in the sample. The first step is to distinguish between B and intermediate A stars; this was accomplished using the precepts of Hilditch *et al.*, and the result is listed in column 2 of Table II (A means intermediate A). Those stars that are too cool for either calibration are noted by NA and have been given the reddening value adopted for the cluster as a whole. In two instances, M808 and M1060, the classifications were ambiguous so values under either assumed spectral type are listed in column 2 and in the notes of column 10. The derived reddening values are listed in column 4. Before discussing the overall mean, a number of extreme values should be mentioned in addition to the above ambiguities. M144, classed as a B star because of its low m_1 index, has an anomalously high reddening of $E(b-y)=0.42$, equivalent to $E(B-V)=0.58$. Aside from the obvious possibility of photometric error, it should be noted that the star is found in the extended halo of the cluster and has a proper-motion probability significantly lower than most of the blue straggler members. A similarly low-probability member, M747, found near the cluster center, holds down the other end of the reddening scale at $E(b-y)=0.169$. M1088 is a confirmed Ap star for which the standard calibrations do not hold. Finally, the *uvby* data for M377 is that of SS transformed to the current system. For the 19 stars classed as members, including all of the above except M1060, a radial-velocity nonmember, and M1088, the derived reddenings lead to a cluster mean of $E(b-y)=0.240\pm0.052$ (s.d.). If the two extremes are dropped from the sample, the remaining 17 stars have a mean of $E(b-y)=0.234$ with a standard deviation for a single star of only ± 0.027. This reddening is equivalent to $E(B-V)=0.32$, essentially the same value derived from the broadband analysis of the stragglers and our simultaneous solution for the reddening and metallicity in Sec. III. We will adopt $E(b-y)=0.23$ for the cluster. Barring the possibility of a purely fortuitous agreement among the various techniques, it appears that the reddening deduced from broad- and intermediate-band photometry of blue stragglers with standard calibrations is reliable.

Before continuing, an intriguing footnote to the question of variable reddening should be made. K1168 (M1054) has $E(b-y)=0.298$, 2.5 σ away from the mean. Breger (1982) has noted only one region of inconsistent polarization in his study of NGC 7789, that involving K970-K1066-K1150-K1168, where the polarization was somewhat lower.

c) Distance Moduli

Given the reddening, it is possible to derive distances for the stars of spectral type intermediate A and cooler. For stars with $-0.02\leqslant(b-y)_0\leqslant0.04$, we have adopted the calibration of Hilditch *et al.* (1983) with $\delta M_V=M_V-M_V$ (ZAMS) $=-10\,\delta c_1$, where $\delta c_1=(c_{1\mathrm{OBS}}-c_{1\mathrm{STAND}})$ evaluated at $(b-y)_0$. For stars with $(b-y)\geqslant0.08$, we have used the standard calibration of Crawford (1979) with $\delta M_V=9$

δc_1. For the transition region, the two standard relations above have been smoothed and $\delta M_V = 9.5\ \delta c_1$. M1251 is an F star and has been evaluated using the calibration of Crawford (1975). The apparent distance moduli were obtained under three different assumptions for the reddening: $E(b-y) = 0.23$ for all stars, $E(b-y) = 0.18$ for all stars, and $E(b-y)$ set equal to the individual values for each star, as discussed above. The results for each case can be found in Table IV. Stars not listed include M99, 172, 210, 238, and 257 because they lie below the standard $c_1 - (b-y)$ relation for all three cases; M511 and 1060 because they are radial-velocity nonmembers; M459, 502, 574, and 913 because they are too hot in the $E(b-y) = 0.23$ and variable reddening cases and fall below the standard $c_1 - (b-y)$ relation for the $E(b-y) = 0.18$ case; and M747 because it is too blue in all instances.

The mean apparent moduli for each case, if all stars are included, are listed in Table IV, ranging from 12.2 to 12.5 with a consistently large standard deviation of ± 0.7. A group of four stars is the major source of the dispersion, M317 and 1251 for all cases, M543 for the variable-reddening and low-reddening cases, and M808 for the low-reddening case. M543 and 808 are either too blue or below the main sequence in the other cases. The mean apparent moduli are also listed in Table IV under the condition that these four stars are removed from the sample. The apparent moduli increase by about 0.1 mag, while as expected, the dispersions decline by about 50% on average. While the inclusion of M808 in the sample is debatable because of its ambiguous status as a B or an A star, it should be noted that the three remaining stars are not a random sample of the blue stragglers in that they have lower-than-average membership probabilities of 76%, 53%, and 71%, indicating that their deviant moduli may represent more than just photometric uncertainty.

Before continuing with the analysis, one point should be clarified. Of the 34 stars listed by McNamara (1980) as blue straggler members (probability greater than 50%), three (M238, 511, 1060) are definite nonmembers based upon radial-velocity results (Hrivnak and Stryker 1984, private communication), five have been characterized as nonmembers using the c_1-$(b-y)$ diagram, and now three more have been identified as possible nonmembers based upon a combination of proper motion and distance moduli, for a total of 11. Since it is likely that more stringent constraints would raise the total, one might justifiably ask whether such a large percentage of interlopers is likely among the stragglers, especially since the average probability for membership is almost 90% among the sample. In an effort to estimate the size of the nonmember population, the following procedure has been adopted. The spread in probabilities within the membership data is due to a combination of field stars with motions comparable to those of the cluster stars, and an inherent dispersion in the measurement of the proper motions. If there is no color dependence on the dispersion of the measurements, the distribution of probabilities for the red giants should be the same as that for the stragglers since they cover a comparable magnitude range, except for the difference in the likelihood of finding a blue interloper compared to that for a red nonmember. The difference in the probability distributions should reflect a difference in the number of field stars along the line of sight.

The distribution probabilities for the stragglers and red giants have been compiled from McNamara and Solomon (1981). Red giants were classed as any star with $B - V \geqslant 1.0$ and $V \leqslant 14.0$. Comparison of the list of stars in BS with that of McNamara (1980) showed that 38 red giants with probabilities greater than 50% were added to the sample of giants under the current classification, while ten stars were not measured by McNamara and Solomon (1981). The probability distribution for the final sample of 93 red giants is plotted in Fig. 7 (solid line); superposed is the distribution for the blue stragglers (dashed line) normalized to the same total of 93 stars. It is obvious that the blue stragglers have a much broader distribution in probability, indicative of a larger percentage of field stars. To get a better estimate of how large this fraction is, it was assumed that the red giants were all members and that the dispersion in the sample represents the dispersion due solely to measurement errors. If we assume that all the stars with probability greater than 95% among the blue stragglers are members, we can renormalize the blue straggler distribution so that there is an equal number of stars in the 95% bin of both samples. The difference in the number of stars in the remaining bins between the two samples is then a measure of the number of the field stars in the blue straggler sample, in this instance equal to $35 \pm 19\%$ of the total blue straggler sample. Thus, the identification of 11 stars as nonmembers out of a sample of 34 does not appear to be excessive.

d) Trends, Anomalies, and Other Curiosities

We now return to the original question of this investigation and attempt to gain some insight into the fundamental nature of the stragglers in the shadow of the limited information garnished from the cluster discussion above. We will focus first on some possible defining characteristics of the stragglers noted by earlier investigators and their applicability to NGC 7789 and close with a discussion of possible trends in the *uvby* data.

As mentioned in Sec. I, one plausible avenue of investigation is to search for a higher-than-average rate of spectroscopic peculiarity among the stragglers in the hope that the nature of the peculiarity among nonblue stragglers would shed some light on their origin. The most comprehensive analysis of this type to date is that of Mermilliod (1982), who looked at 30 blue stragglers in 75 open clusters younger than

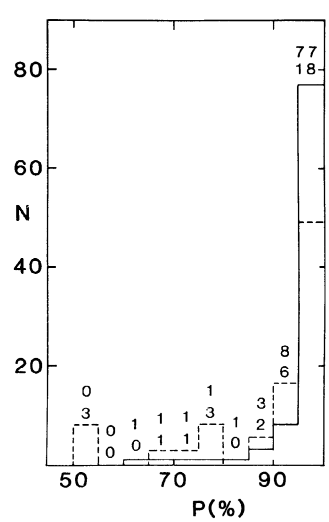

FIG. 7. Membership probability distribution for red giants (solid line) and blue stragglers (dashed line) from the data of McNamara and Solomon (1981). Totals are normalized to 93, while the numbers above each bin give the actual number of red giants (upper number) and blue stragglers (lower number) in each bin.

the Hyades, i.e., significantly younger than NGC 7789. Mermilliod found that while the rate of spectral peculiarities was high (50%), this is typical of nonblue stragglers of the same spectral type. Moreover, the type of peculiarity (Be, Bp, Am, etc.) was no different from that found in a random sample of field stars. Thus, whatever the source of these anomalies, they have little bearing on blue straggler production for early-type stars. If this trend holds for blue stragglers in older clusters, NGC 7789 should show a percentage of Ap and Am stars, the most common types of peculiarity in the A0 to F0 range, nearing 25%, equally divided between the two (Abt 1979). For the 30 stars in Table III, only one has *uvby* indices indicative of an Ap star, M1088, corroborating an earlier spectral classification of this star by Stryker and Hrivnak (1984). For Am stars, the m_1-$(b-y)$ relation is plotted in Fig. 8 with a reddening correction of $E(b-y) = 0.23$ applied. The figure reveals that a number of stars lie in anomalous positions relative to the standard curve, most with low m_1 indices for their colors. These stars (M144, 325, 808, 1054, 1142) are those noted in Table III as having ambiguous or extreme reddening values for this very reason. Only one star (M913) has indices typical of an Am star. Since six to eight stars were expected to fall into the Ap-Am category, it appears that there is a deficiency of peculiar stars among the blue stragglers in the cluster. However, since such classifications are defined spectroscopically, it would be wise to verify the result in this manner rather than relying on possibly inadequate photometric criteria.

One of the more unexpected results in the study of blue stragglers in clusters was the discovery by McNamara (1980) of an extended halo of stragglers in NGC 7789. Though a number of these stars have been classed as nonmembers on photometric grounds in earlier sections, it is illuminating to detail the implications of their membership in the cluster, should future work invalidate their exclusion from the sample. McNamara (1980) investigated the origin of the stragglers by dividing his sample into red giants and main-sequence stars and plotting the radial distribution in the cluster. The apparent trend was one of a decreasing degree of central concentration in going from red giants to stragglers to main-sequence stars. Because the red giants evolve from stars more massive than those still on the main sequence, McNamara interpreted the trend as evidence in support of the binary mass transfer hypothesis. The intermediate radial distribution of the stragglers implied an origin from stars of mass intermediate between the red giants and the main sequence, i.e., the turnoff and subgiant branch. If mass transfer is most probable when one member of the binary evolves toward the red giant stage, mass-transfer stragglers should come predominantly from the turnoff and subgiant populations. This argument is invalid for two reasons, one definite and one debatable. If the stragglers are binaries, their radial distribution is defined by the total mass of the system, not the individual masses. Thus, if the straggler systems have total masses which are, on average, 50% larger than the single turnoff star, they should be much more strongly concentrated in the cluster than the giants or main-sequence stars. Second, the giants evolve from the most massive stars visible in the cluster, but mass loss on the giant branch will lead to a redistribution of these stars within the cluster. Though evidence for such a redistribution has been claimed for a number of clusters older than NGC 7789 (McClure and Twarog 1977; Hawarden 1975), acceptance of the reality of the effect is far from universal. For the case of NGC 7789, the work of Hopp (1980) indicates that mass loss has not had a major effect on the radial distribution of the giants. The giants, turnoff stars, and main-sequence stars are increasingly less concentrated toward the cluster center, implying that the radial distribution can be used as an accurate measure of the stellar mass for a given class of stars.

Because of the expanded sample of giants mentioned in Sec. II*c*, a reanalysis of the radial stellar distribution was undertaken. The surface density of red giants as a function of radial distance from the center of the cluster is given by the solid line of Fig. 9 with a total sample of 93 stars. The radial distance is in the arbitrary (x, y) units of McNamara and Solomon (1981). For comparison, a long-dashed line shows the same information for 31 blue stragglers from McNamara (1980), all with membership probability greater than 50%, including M1251, M1368, and the stars noted in Table III as probable nonmembers based upon radial-velocity and/or photometric data. Even with the larger statistical uncertainty in the blue straggler sample, it is difficult to avoid the

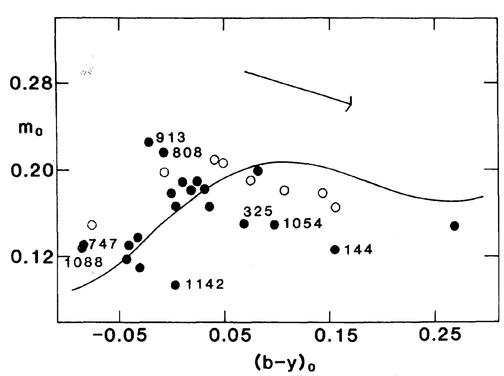

FIG. 8. Same as Fig. 6 for m_0-$(b-y)_0$. Potentially anomalous stars are noted by their identification numbers on the system of McNamara and Solomon (1981).

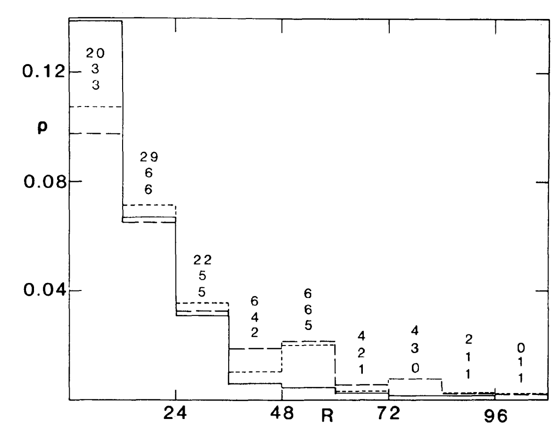

FIG. 9. Radial surface density distribution for red giants (solid line), blue stragglers with membership probabilities greater than 50%, excluding all other criteria (long-dashed line), and blue stragglers with nonmembers as noted in Table III excluded (short-dashed line). All distributions are normalized to the same total surface density. The numbers above each bin give the actual number of stars in the bin in the order red giants (upper number), all blue stragglers (middle number), and blue stragglers with nonmembers removed (lower number).

conclusion that the stragglers are less centrally concentrated than the giants. Thus, if these stars are all members, it would place severe constraints on any model of binary mass transfer as the source of the stragglers. [As evidence of the fact that such a model cannot be eliminated even if the above radial gradients are corrected, the reader is referred to the discussion of Peterson, Carney, and Latham (1984).] If one takes the plausible view that the stars as noted in Table III are nonmembers, the resulting distribution for the 24 remaining stragglers reduces to the short-dashed line of Fig. 9. Since most of the excluded stars are in the cluster halo, as expected, the central concentration of the stragglers increases to the point where it is comparable to that of the giants within the accuracy of the data. (In all three cases, the plots are normalized so that the total surface density is the same.) A more quantitative estimate of the reality of the apparent distribution differences exhibited in Fig. 9 can be gained from the median radial distance for the three samples. For the giants, the median distance is 22.6; for the blue stragglers, all stars included, the value is 43.0, and with probable nonmembers excluded it drops to 32.0. In short, the current data suggest that the radial distribution of the stragglers is equivalent to that of the red giants, if not less centrally concentrated. Unless binary formation is radially dependent, the stragglers come from the same mass ranges as the giants, i.e., single stars near the cluster turnoff.

Finally, since the m_1-$(b-y)$ data have failed to provide a distinctive trademark for recognition of the stragglers, we are left with the c_1 data, where only a portion of the stars are cool enough to exhibit surface-gravity effects. Among these stars, the most common characteristic is the large δc_1 index indicating a lower-than-average surface gravity by $\Delta \log g \cong 0.5$ (Relyea and Kurucz 1978). From the cm diagram, the stragglers lie typically 1.0 to 1.5 mag above the ZAMS, with only three lying within 0.5 mag of the main sequence. This pattern is in excellent agreement with that found by Mermilliod (1982) among the hotter blue stragglers, where only three of 39 stars are found within 0.5 mag of the ZAMS and most lie within 1.0 to 1.5 mag above the ZAMS. The upper limit for both samples is the terminal age main sequence (TAMS). For NGC 7789, the reality of the boundary as noted by Saio and Wheeler (1980) has been confirmed by the proper-motion study of McNamara and Solomon (1981) and the polarization study of Breger (1982), which eliminated most of the redder stars from membership.

While it is often stated that the position of the stragglers is indicative of post-ZAMS evolution, it is important to recognize that this is only by analogy to normal stars in the same region of the cm diagram. For mass-transfer binaries, the secondary star undergoes an increase in its total mass, which leads to more rapid evolution. Since it is likely to be of a mass comparable to the primary prior to transfer, it will already be partially evolved. The probability of finding an unevolved straggler would be small and the distribution in the cm diagram would be just what is described above. If, as claimed above, the stragglers are single stars, the surface-gravity distribution could be evidence for a more fundamental effect than simple evolution. First, it makes it highly unlikely that the stragglers represent secondary formation unless this process is a continuous one. A secondary burst should produce stragglers which lie on a common isochrone; this is clearly not the case. Second, if the internal structure of the star has been altered in some fashion to prolong the main-sequence life of the star, then the distribution in surface gravity will be a reflection of two effects, a shift in the ZAMS due to the internal mechanism, and normal evolution away from the redefined ZAMS. If the paucity of stragglers within 0.5 mag of the ZAMS (less than 10% of the sample) represents a true physical boundary, then the redefined ZAMS for the stragglers is one of lower-than-normal surface gravity. The best current explanation of the extended stellar lifetime consistent with this argument is a mixed model induced by rapid core rotation as in Saio and Wheeler (1980).

V. CONCLUSIONS AND FUTURE PROSPECTS

In an effort to learn something about the nature of blue stragglers, *uvby* photometry of 28 possible members of the open cluster NGC 7789 has been obtained and analyzed. To place the stragglers in the proper context, a rediscussion of the fundamental cluster parameters has been attempted with the result that $E(B-V) = 0.31 \pm 0.03$, [Fe/H] relative to the Hyades $= -0.25 \pm 0.10$, $(m-M) = 12.3 \pm 0.3$, and the age is $1.6 \pm 0.5 \times 10^9$ on the isochrone scale of Ciardullo and Demarque (1977). Within the large uncertainties, when applied to the blue stragglers, standard photometric calibrations provide distance and reddening values consistent with those based upon normal stars. Using a combination of radial-velocity data, position in the c_0-$(b-y)_0$ diagram, and distance moduli, it is estimated that at least 11 of the possible member blue stragglers are field stars. More importantly, a significant fraction of these interlopers populate the extended halo of the cluster as delineated by McNamara (1980). Even with these stars excluded from the sample, the radial distribution of the stragglers is found to be equivalent to that of the red giants, indicating that the masses of the stragglers are similar to those of the red giant progenitors, i.e., single stars near the cluster turnoff, in contradiction with the earlier conclusions of McNamara (1980). The one possible, direct clue to the nature of the stragglers provided by the *uvby* photometry is a tendency toward surface gravities that are about 0.5 smaller in log *g* than those for stars on the ZAMS. The distribution in the cm diagram gives weak evidence for a possible lower bound to the luminosity of the stragglers located about 0.5 mag above the ZAMS, in agreement with earlier data of Mermilliod (1982) on hotter blue stragglers. When combined with the single star requirement claimed above, this constraint leads to a conclusion that the current model which best fits the available information on blue stragglers is that of the mixed, main-sequence star, possibly induced by rapid core rotation, as discussed by Saio and Wheeler (1980).

While it could be argued that the only definitive conclusion of this investigation is that it has no definitive conclusion and that a twenty-year-old astrophysical enigma is unlikely to be resolved by any single observational program, it is felt that some new directions for future research have been noted, while others have been given new emphasis.

First, the growing evidence that the blue stragglers of the disk cannot be distinguished from normal stars of the same spectral type through standard photometric and spectroscopic techniques ties the unravelling of their nature to their role in open clusters. If a pattern exists, it must be delineated within the context of the clusters in which the stragglers are found. The ability to learn about the stragglers is limited by the quality of the data available on the clusters they inhabit. NGC 7789 is a classic example of the problem. It is one of only a dozen or so open clusters older than the Hyades and, along with NGC 2158, is one of the richest in members. Its age, richness, and supposedly low metallicity have led to its use as a standard comparison cluster for intermediate age, globular clusters in the Magellenic Clouds, while its position beyond the solar circle has made it a valuable point in defining the metallicity gradient of the disk. Despite this, no comprehensive photometric survey has been done of the cluster since the original study of BS, 27 years ago, based on a total of only two plates in each color, which failed to reach the unevolved main sequence. As is apparent from the discussion in this investigation, the reddening, metallicity, and distance are known with only rough certainty. Compared to most clusters, the membership status for stars in the cluster is remarkably good since the proper-motion work extends just to the turnoff, and radial-velocity data are available for a portion of the stragglers. Until the situation improves for a large sample of open clusters, significant progress in understanding the blue stragglers will be slow in coming.

Second, given that our understanding of open clusters must be improved to understand the blue stragglers, the most likely avenues for success as indicated by this investigation are: (a) The obvious need for an increase in the number of clusters with both proper-motion membership and radial-velocity work. The extended halo stragglers in NGC 7789 are proof of the dangers of relying on proper-motion data alone. The fine start made by Peterson *et al.* (1984) and Stryker and Hrivnak (1984) should be continued and expanded to fainter, normal main-sequence stars whenever possible. (b) Given reliable membership information, the one clue that may decide the true nature of the stragglers is the radial distribution within open clusters. If the trend found in NGC 7789 can be confirmed in other clusters, binary mass transfer models would be increasingly constrained. It is important to note that the small number statistics for stragglers in most clusters will permit a successful conclusion along this line only if the data from a large sample of clusters can be combined. Age effects must also be considered and comparisons should only be made with main-sequence stars for the older clusters. For the older clusters, the existence of a concentration of stragglers when compared to red giants might reflect a radial redistribution of the red giants that have undergone mass loss rather than a significant concentration of blue stragglers toward the cluster center. (c) If reliable reddening, metallicity, and distance information is available, the combined data for a number of clusters would provide a definitive test of the distribution of the stragglers in the cm diagram and the reality of the lower limit in luminosity noted above, continuing the excellent start provided by the work of Mermilliod (1982).

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